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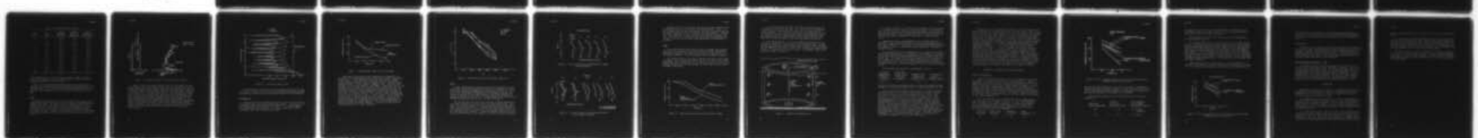

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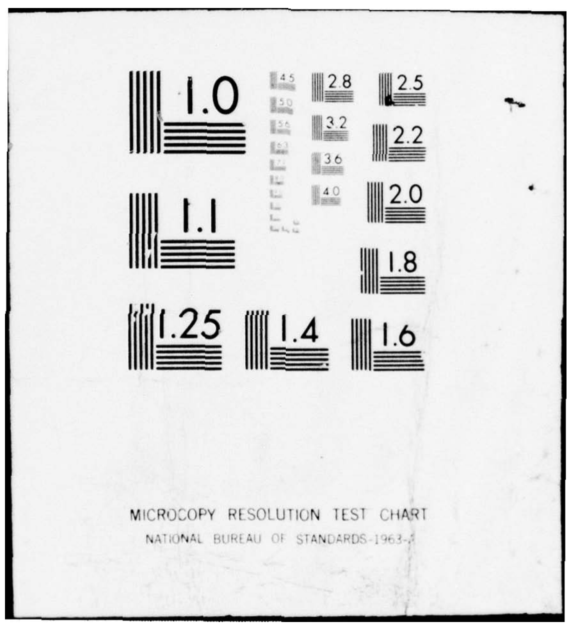
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Propagation and Reverberation in Shallow Water for a Vertical Array and Single Transducer – Implications in Sonar Operation

Louis A. King, Ralph W. Carone, Horst Zachow
Ocean Sciences and Technology Department

21 March 1977

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PREFACE

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The results of a Shallow Water Echo and Reverberation Experiment (SWERE) performed in September 1975 in a flat-bottom, shallow-water, acoustic range located in Block Island Sound are reported. The experiment is part of an effort to develop the concept of Mode Enhancement Techniques (transmitting or receiving techniques for enhancing modes to improve signal-to-background levels in shallow water). Consequently, the results are interpreted in terms of normal mode theory

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20. Abstract

Compared are the depth and range structures of the out-going signal field and reverberation produced by a vertical array and a single transducer, both driven with equal input power at a frequency of 1700 Hz.

It is shown that for the array, the peak- and depth-averaged signal levels decay at a rate of -4 dB per distance octave (distance doubled) in contrast to the rate of -11.3 dB per distance octave for the single transducer.

The depth-averaged reverberation levels for the array are 4 dB greater, but decay at approximately the same rate, -13.5 dB per distance octave, as for the single transducer.

By using the above decay rates and reasonable target strength values to calculate echo-to-reverberation and echo-to-noise levels, it is shown that a vertical array can markedly increase the potential for detection in shallow water over that of a single transducer.

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INTRODUCTION

Shipboard sonar systems deployed in deep water usually use mechanical or electrical steering techniques to obtain bearing and depression angles to a signal source. When these sonar systems are used in shallow water, the inherent multi-path conditions degrade their performance. However, viewing the acoustic problem in terms of mode theory leads to a concept which can improve or optimize system performance. This concept, termed Mode Enhancement Techniques (METS)[1,2] is based on using modal properties of sound in shallow water to improve the efficiency of transmitting a signal and to increase the signal-to-background levels of a received signal.

A series of Shallow Water Echo and Reverberation Experiments (SWERE) is planned to explore further the METS concept. Several configurations of a vertical transmitting array were used to obtain data for the range and depth structure of the intensity and coherence of echoes and reverberation. One aspect of this series is to determine the gains in echo-to-background level obtainable using various configurations of a vertical array rather than a single transducer.

Reported here are the results of a SWERE made in September 1975 for an acoustic frequency of 1700 Hz. It is shown that when equal input power is applied to a vertical array and a single transducer, the sound-level averaged over the water column (this is proportional to the acoustic energy conducted by the channel) is greater for the array. It is also shown that the decay rate of the sound levels with increasing range is much less for the array case than for the single transducer. The decay rate of reverberation with increasing range (or time), however, is shown to be similar for both the array and single transducer. The implication of these results in sonar operation is brought out in the discussion where it is shown that for a reasonable target strength value, a vertical array can increase the potential for detection in shallow water over that of a single transducer by improving the echo-to-background levels.

MEASUREMENT DESCRIPTION

The normal-mode-tower,[3] a vertical array of transducers one-half kilometer west (see figure 1) of Block Island, was used to transmit sound and to receive the reverberant acoustic energy.

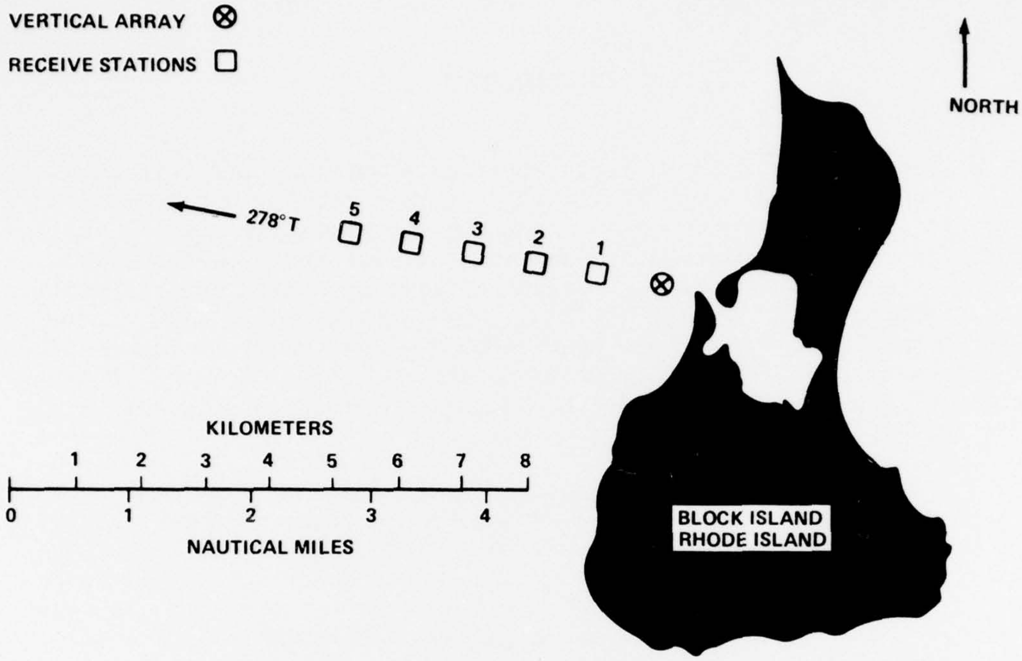

Figure 1. Experiment Diagram

The signal and reverberation fields produced by four different transmitting configurations of the array were recorded and analyzed. The configurations used were cosine and uniform weighting of 11 elements centered at mid-depth, a single element near the surface, and a single element at mid-depth (see figure 2). The total input electrical power for each configuration was made equal. This made the same available acoustic power common to all results. A CW pulse of 1700 Hz, and 200 millisecond (msec) pulse length was used for the reverberation measurements.

Scientists aboard the receiving ship, a landing craft utility (LCU) measured the vertical acoustic field, temperature profile, and water depth at five range stations along a 278° radial from the normal-mode-tower (see figure 1). The sound-pressure level and water temperature were recorded for every 5 foot (1.52 m) depth interval of the water column. The water depth along this track is fairly uniform; it ranges from 101.7 feet (31 m) at the tower to 109.9 feet (33.5 m) at the farthest station 1.6 nmi (2.5 kilometers), and remains 113.2 $\pm$ 3 feet

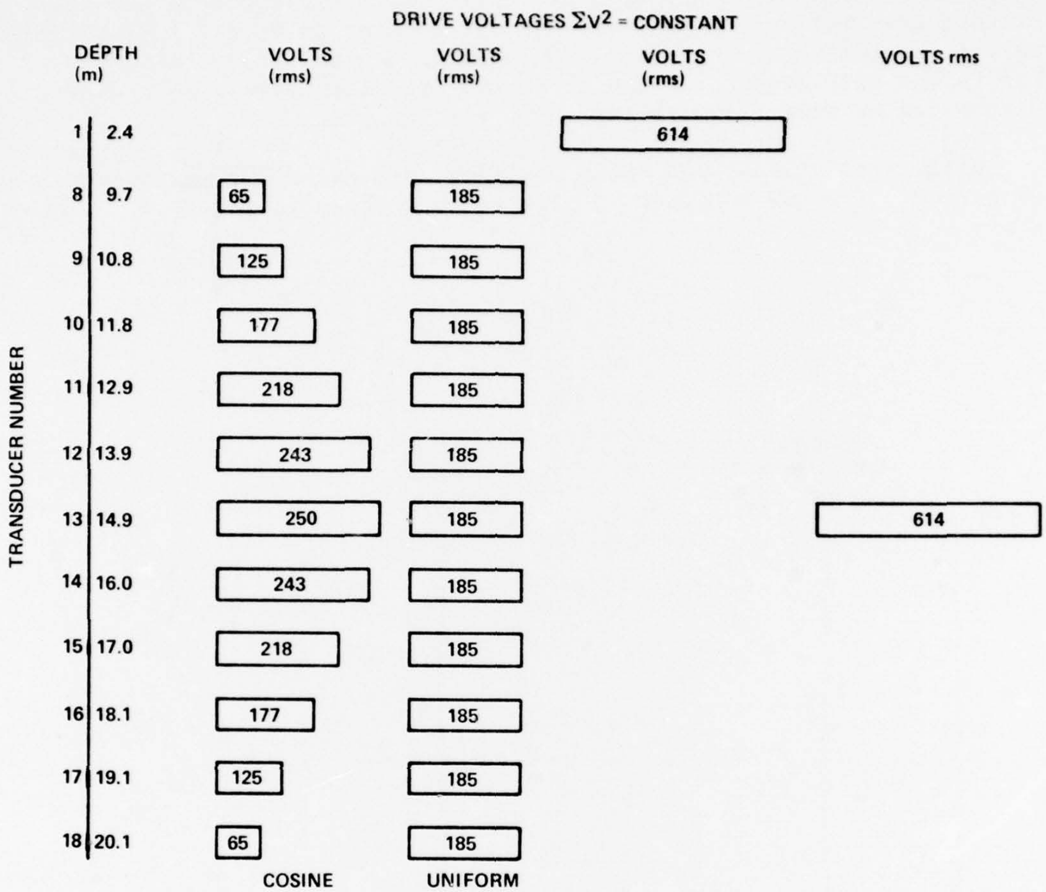

Figure 2. Array Configurations

(34.5 $\pm$1 m) for approximately 9.1 nmi (14.6 km) thereafter. At each station a tri-plane target was suspended at a water depth of 49.2 feet (15 m). During the first day the source level of the mid-depth element and the target strength of the tri-plane were measured (unfortunately the target strength proved to be inadequate for the planned echo measurements).

Since the electronic equipment aboard the LCU required a pulse length of 400 msec, each event was divided into two parts. Scientists at the shore station recorded the reverberation produced by 200 msec

pulses; then transmitted 400 msec pulses for scientists aboard the LCU to record the vertical sound field. After completion of one full set of transmitting configurations, the LCU would then proceed one-half kilometer to the next station. Wind speed and direction were also measured and recorded by scientists at the shore station.

Fairly stable iso-sound speed profiles, prevailed during the measurement period. Typical sound speed profiles are shown in figure 3.

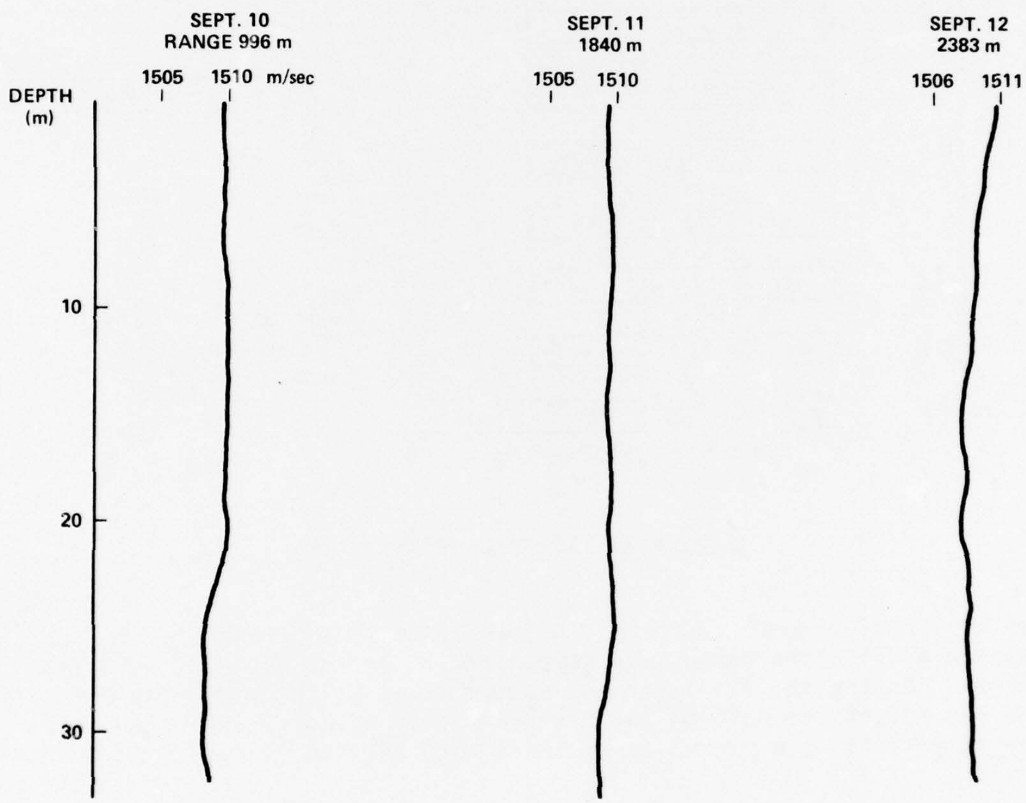

Figure 3. Typical Sound Speed Profiles

DATA RESULTS

SIGNAL FIELD

Depth

The vertical structure and spread in values of the sound pressure field as measured at each range are shown in figure 4. The upper series is for a uniform weighting of the array, and the lower is for a single transducer located at mid-depth. These results are representative of the vertical sound-pressure fields produced by the four transmitting configurations, all having the same input power.

The major differences in the vertical fields produced by the two configurations are that the array-generated field is smoother than the ragged single-transducer generated field, and that the maximum levels for the array case are approximately 7-8 dB greater than the maximum levels for the single-transducer case.

The smoother field suggests a predominance of low order modes, while the ragged structure indicates a predominance of high order modes. This is born out in figure 5, which compares the computed vertical structure of the transmission loss curves for a single transducer and a uniformly weighted array. The given structure consists of 10 modes calculated for the given sound speed profile and element depths, and summed to give the loss as a function of depth, for a range of 6037 feet (1840 m). In the case of the single transducer, the excitation factors foe each mode are equal and the result is a ragged curve – shown as the solid transmission loss curve. For the array, the excitation factors heavily weight the low order modes, resulting in a smoother curve – shown as the dashed curve. It is also seen that the computed amplitudes of the low order modes, being greater for the array case, produce maximum levels in regions of constructive interference 7 to 8 dB greater than the single transducer case.

The directionality of the array (represented by its beam pattern) can be related to the observed results by associating directional source levels to the preferred angles of propagation associated with the modes. For a constant frequency, the lower order of mode, grazing angles of the wave trains producing the mode are shallower. The mode angles for 10 modes were calculated and are presented in table 1. Mode related source levels for the various configurations, as obtained from the directional source level curves shown in figure 6, are also presented in table 1. It is evident from table 1 that the single transducer directs energy equally to all modes. The uniform and cosine weightings,

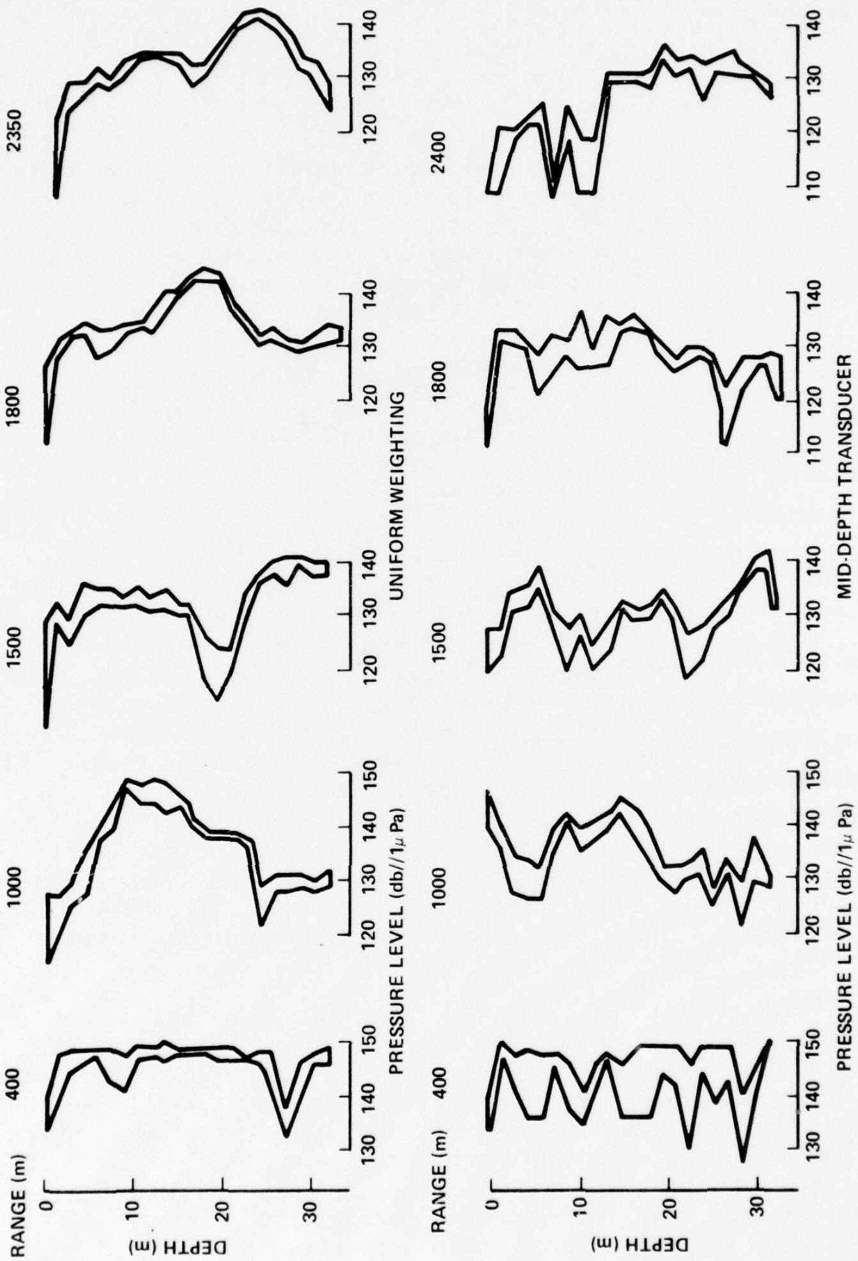

Figure 4. Vertical Structure of Signal Levels

Table 1. Mode-Related Source Levels

Mode No.	Mode Angle	Single Transducer (dB//1μPa)	Uniform Weighting (dB//1μPa)	Cosine Weighting (dB//1μPa)
1	2^o	190.2	197.7	198.3
2	2.3^o	190.2	196.3	197.5
3	2.9^o	190.2	193.7	195.5
4	3.6^o	190.2	187.9	192.4
5	4.3^o	190.2	177.7	189.8
6	5.1^o	190.2	180.2	184.3
7	5.9^o	190.2	187.0	167.3
8	6.7^o	190.2	187.3	172.3
9	7.6^o	190.2	180.2	177.7
10	8.5^o	190.2	178.2	176.7

on the other hand, "steer" more of the available energy into grazing angles corresponding to low order modes – modes 1-3 for the former weighting, and modes 1-4 for the latter.

Thus, it is seen from the mode and beam pattern considerations, in agreement with observed results, that the vertical array enhances the low order modes, and has the potential of generating greater peak levels than the single transducer by the constructive interference of these modes.

Range

In addition to studying the vertical structure of the signal field, comparison was made of the total acoustic energy each configuration provided at each range. The squared pressure, averaged over the water column, was used as a measure of the total acoustic energy. The two resulting "array" curves, being similar, were averaged to produce a representative curve. Similarly a representative curve was obtained for the single transducer results. Both representative curves are shown in figure 7.

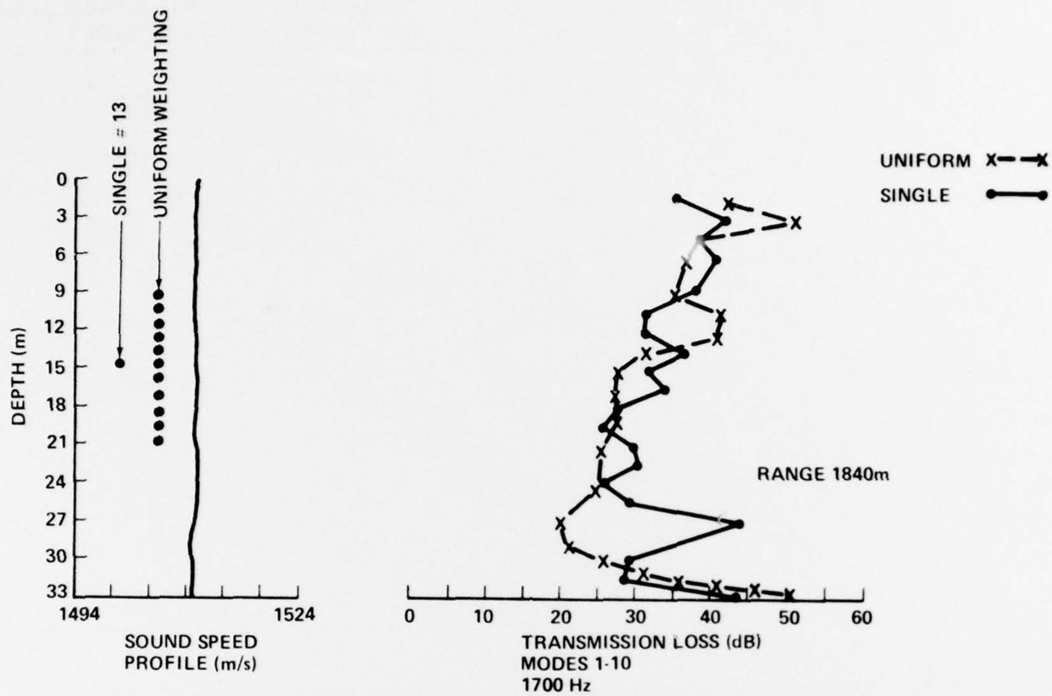

Figure 5. Vertical Structure of Transmission Loss (Model)

Both the array and single transducer have initially about the same total energy. These values decay at the same rate to 3281 feet (1000 m). Beyond this range, the array levels remain greater and decay at a rate of -4 dB per distance octave (distance doubled), while the single transducer levels decay at -11.3 dB per distance octave. The difference in slopes indicates that the low-order modes comprising the field produced by the array suffered less loss with increasing range than did the high-order modes predominating the field produced by the single transducer. The array, by enhancing the low order modes (modes favored by the propagation conditions) was more efficient in transmitting signal energy than the single transducer. Thus, of the two, the vertical array has the greater potential of transmitting more of the available acoustic energy to longer ranges.

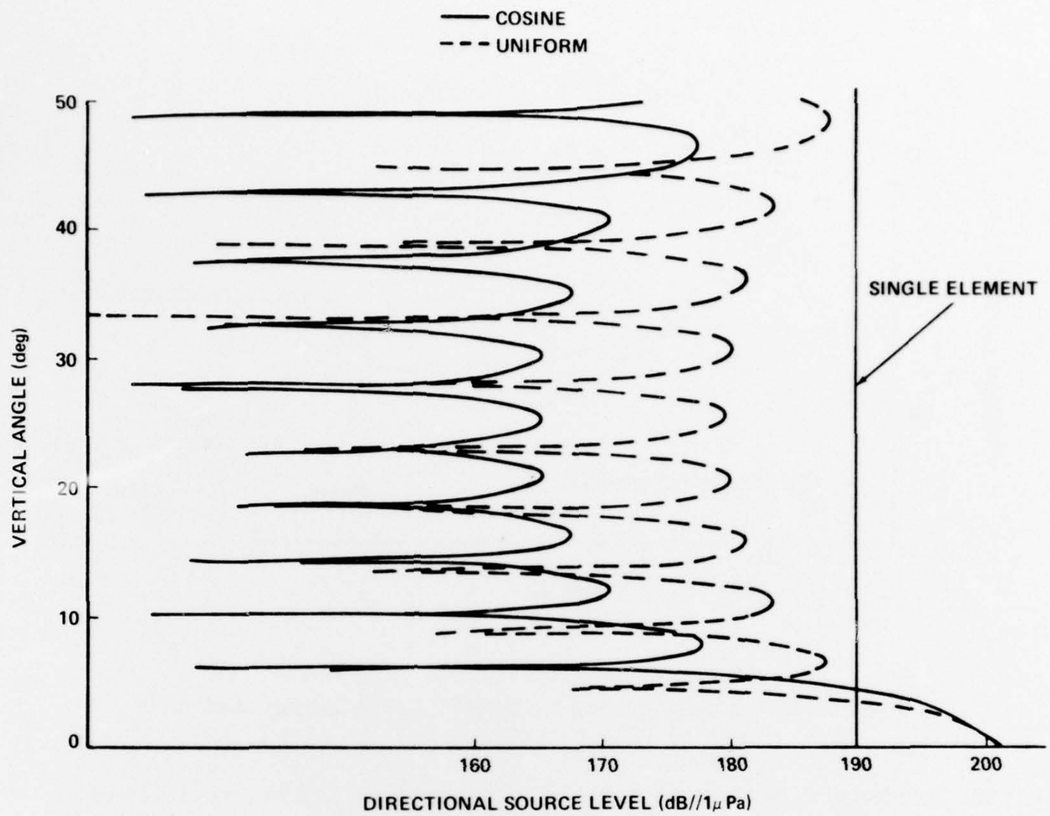

Figure 6. Directional Source Level

The experimental and theoretical results demonstrate that for equal input power, a vertical array has greater potential for producing higher average and peak signal levels at longer ranges than does a single transducer.

REVERBERATION

The potential for increasing signal level is not the only technical consideration that enters sonar design and operation. The potential to discriminate against reverberation is another. This section compares the reverberation levels produced by a vertical array and a single transducer, where both have equal input power.

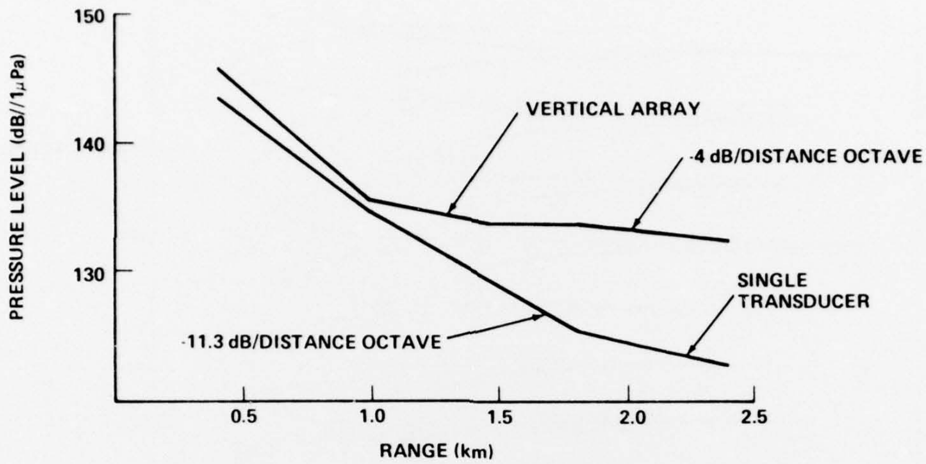

Figure 7. Depth-Average Signal Level Versus Range

Reverberation generated by each transmitting configuration was received at the normal-mode-tower on hydrophones located at eleven different depths. The hydrophone outputs were simultaneously bandpass filtered (center frequency 1700 Hz, bandwidth 200 Hz), amplified, and analog recorded on eleven channels of magnetic tape. The data, upon playback, were envelope detected, transformed to logarithmic values, and recorded on strip charts with 20 msec of time constant inserted. The resultant curves were further simplified by taking discrete values at one-second intervals (this corresponds to one-way range increments of 750 m) out to 5 seconds (3750 m). This was done for the reverberation histories for 10 consecutive pulses. The 10 values for each range were averaged, and the average values connected linearly. A plot of four linear-segmented curves representing the reverberation measured as a function of range at a fixed depth for each of the configurations was used as the basis for further analysis. A typical plot of the basic reverberation curves is shown in figure 8.

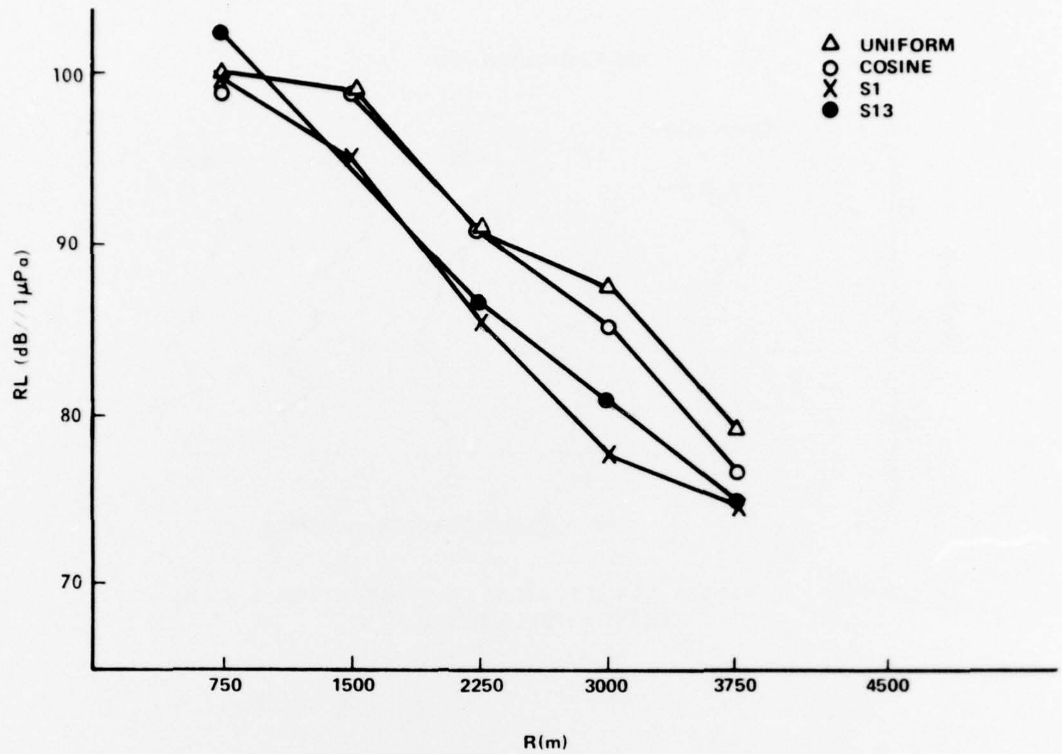

Figure 8. Reverberation Level Versus Range, Depth 15 m

Depth

Graphs containing the vertical structure of reverberation at each of the five ranges were generated from the basic reverberation curves. Since there were four configurations and five date-time series, a four-row by five column matrix arrangement of these graphs represents the vertical structure at each range produced by any given configuration, during any given date-time series. A graph element of the matrix for the uniform configuration for one series is shown in figure 9.

For any one date-time series, the vertical structures generated by the single transducers are very similar in variation and level. Similarly, the vertical structure for the uniform and cosine weightings are alike. For convenience then, the uniform case and the mid-transducers case (denoted as S13) were selected to represent and compare results for the array and single transducer. Figure 10 compares the vertical structures of reverberation at each range for the array and signal transducer.

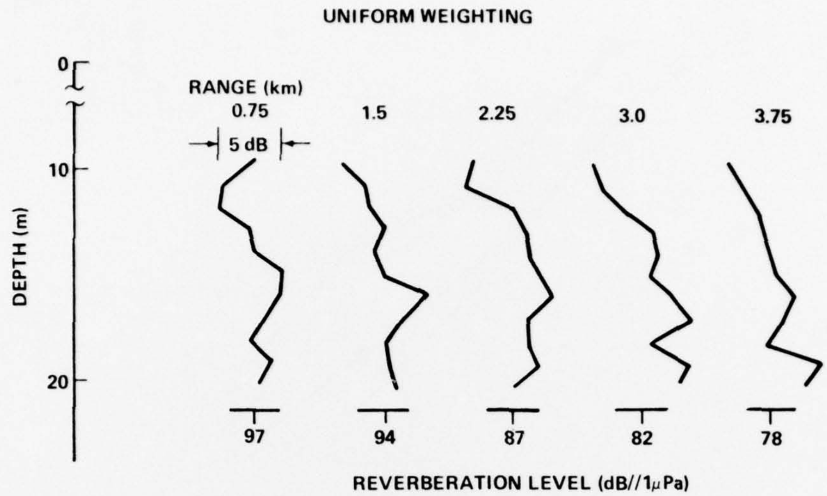

Figure 9. Vertical Structure of Reverberation 5 Ranges Uniform Weighting

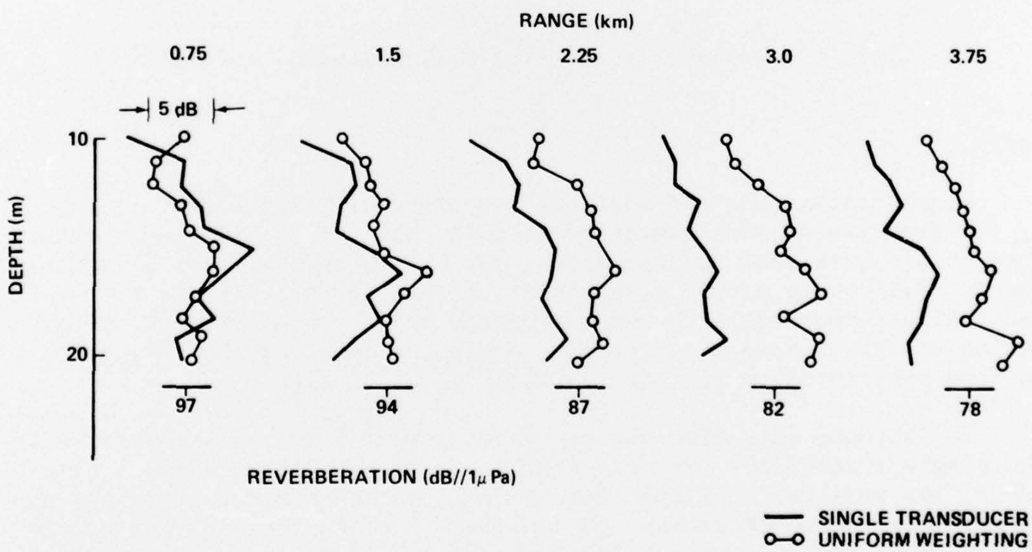

Figure 10. Vertical Structure of Reverberation-Array Versus Single Transducer

Inspection of any one of these structures show depth-segments where minimum levels may be 5 to 8 dB less than maximum levels. Also, it is quite evident that the levels produced by the array are greater than for the single transducer everywhere over the receiving aperture. Although the levels differ for the two, the curves are similar in general structure. The similarity, irrespective of the transmitting configuration, is used in the next section where range dependence of reverberation is discussed.

Range

As was done for the signal field, vertical averages were obtained from the basic reverberation curves to produce one curve representing reverberation energy versus range for the vertical array and one for the single transducer. The two resulting curves are shown in figure 11.

The average level for the array is greater than that for the single transducer. Clear trends occur beyond .92 nmi (1.5 km) in that both curves decay at an average rate of -13.5 dB per distance octave (distance doubled) and that with increasing range the values for the array remain uniformly 4 dB greater.

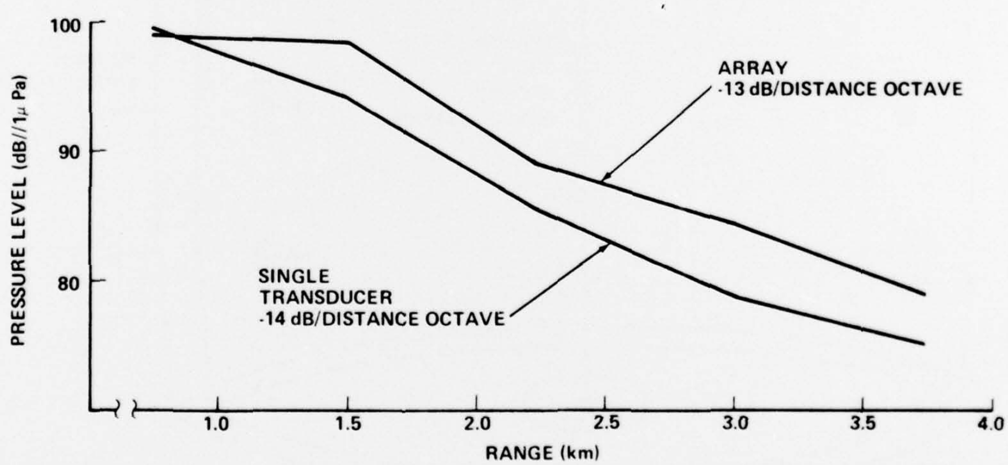

Figure 11. Depth-Average Reverberation Level Versus Range

It is seen from both the depth and range results that decay of reverberation with increasing range is the same for both transmitting configurations, albeit the level is greater for an array than for a single transducer. Why should the decay rates of reverberation be similar, when the incident signal energies decay at much different rates? Why should the average reverberation levels be greater for the array than for the single transducer, when both have equal input powers?

In way of explanation, it is first assumed that generally the reverberation energy (or level) depends on the incident energy, the propagation loss of energy, and the nature of the scatterers. These relations are now adapted to the present shallow water situation for ranges beyond .93 nmi (1.5 km) for the case of the array. The geometry used for the adaption is shown in figure 12.

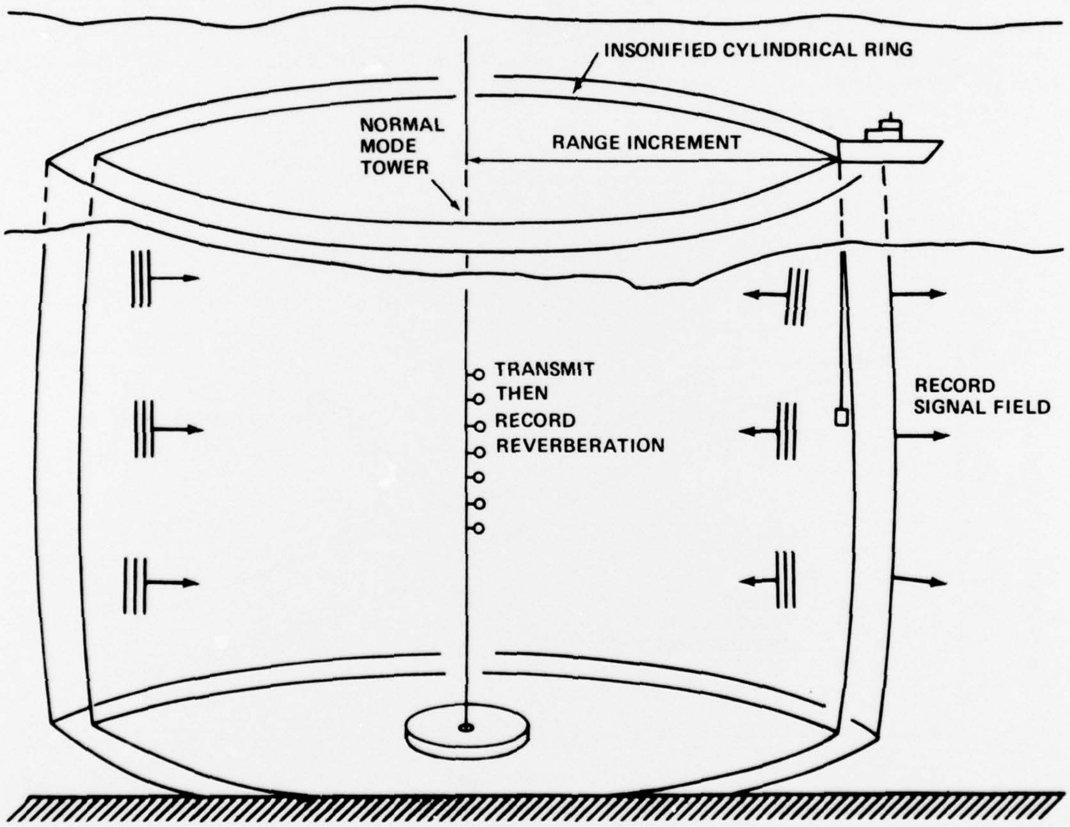

Figure 12. Geometry for Reverberation

The energy incident on a sector of the cylindrical ring (see figure 12) is predominantly the energy in the low-order modes. The reverberation level and its decay with range should then depend on the level and decay of these modes. Used as a measure of decay, is the decay rate of the low order mode field produced by the array (-4 dB per distance octave).

From any one sector, the propagation loss of reverberation as a function of range should be similar to that of the multi-mode field of the single transducer. Consequently, an estimate of the propagation loss with range is taken to be that of the single transducer (-11.3 dB per distance octave).

The reverberation level is proportional to the number of scatterers within the insonified ring. If the density of the scatterers is uniform, the reverberation level becomes proportional to the volume of the cylindrical ring. The volume of this ring is proportional to the radius of the cylinder; the radius being the range from the source to annulus of the cylindrical ring. Thus, the level is proportional to the range, r, and would increase with increasing range as 10 log r or 3 dB per distance octave.

The resulting rate of decay in reverberation level is

Net Decay Reverberation (dB/distance octave)	=	Decay Rate Incident Energy (dB/distance octave)	+	Propagation loss vs Range (dB/distance oct.)	+	Increasing Rate Scatters (dB/dist. oct.)
-12.3	=	-4	+	-11.3	+	+3

The net decay rate of reverberation for the array as observed from measurements is -13.5 dB per distance octave — a difference of only 1.2 dB.

If one carries out the above calculations for a single transducer and uses a value of -11.3 dB per distance doubled for both the decay rate of the incident energy and the propagation loss versus range, the result is a net decay of -19.6 dB per distance octave. The decay rate of reverberation for the single transducer case observed from measurements is -13.5 dB per distance octave. Thus, the same considerations lead to a much greater discrepancy with the measured results. The observed similarity in value of the decay rate of reverberation for the single transducer and the array suggests that it is the low-order mode content in the incident energy that contributes most. The steeper rate of -19.6 dB per distance octave would result from the high-order mode content of the incident energy. This rate leads to no discrepancy; it is just not observable because it is masked by the reverberation produced by the low-order mode content.

The decay rates of reverberation for both the array and single transducer configurations are approximately the same, but actual levels for the array are greater by 4 dB (see figure 11). The difference may occur because the level of low order mode content for the array is greater. The predominance of the low order mode content in the array field is evident from experimental and computed results. An estimate of the actual difference in low order mode content produced by the array and single transducer configurations is obtained heuristically by determining the difference of the average mode-related source level of the low order modes for each configuration. Referring to table 1, the average level for the first three modes of the uniform pattern is 196 dB; for the first four modes of the cosine pattern, 196 dB; and for the single transducer, 190 dB. The level of low order mode content for either array shading is 6 dB greater than the content for the single transducer. Thus, the difference in low order mode content of the incident energy is of the right order of magnitude; however, to determine the difference in absolute reverberation levels would require an expression, empirical or otherwise, for the direct relation between the incident energy and the reverberation sector – in other words, a reverberation "strength" for each mode is required. Further experimental and theoretical work on this aspect is planned.

DISCUSSION – IMPLICATIONS IN SONAR OPERATIONS

ECHO TO REVERBERATION

Figure 13 illustrates the gain in echo to reverberation levels one may achieve with an array rather than a single transducer. Shown for comparison are linearized curves of echo and reverberation levels as a function of range for a vertical array and single transducer. To calculate the echo levels (unfortunately actual echo levels could not be obtained since the tri-plane target deployed in the experiment had an insufficient target strength for any echo measurements) a target strength of 15 dB at 3.3 feet (1 m) is assumed. The echo is assumed to consist of many modes and to propagate like the multi-mode signal field produced by the single transducer.

First, the echo levels are determined for the two configurations when the target is at a range of .93 nmi (1.5 km). The propagation loss in the case of the single transducer is calculated for equation (1) by subtracting the depth average signal level at 1.5 km (129 db//1 μPa) from the single transducer source level (182 dB//1 μPa). The echo level using the single transducer is

$$\underline{\text{Echo level dB//1}\,\mu\text{Pa}} = \underline{\text{Source level dB//1}\,\mu\text{Pa}} - \underline{2 \cdot \text{Propagation loss dB}} + \underline{\text{Target Strength dB}}\,. \quad (1)$$

$$91 = 182 - 2 \cdot 53 + 15$$

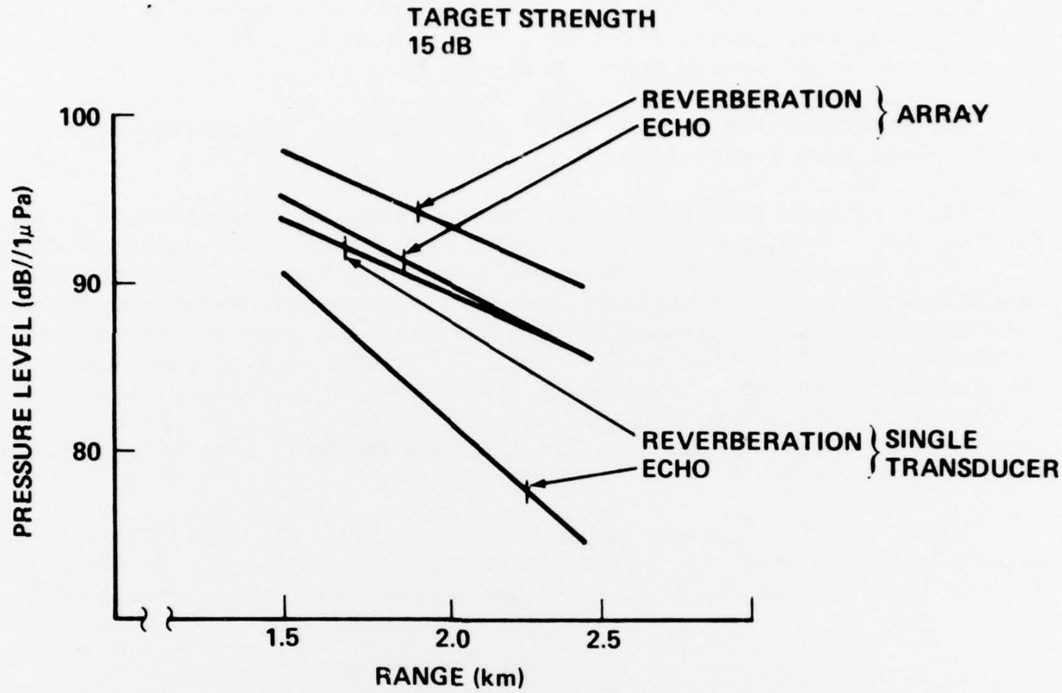

Figure 13. Echo to Reverberation Level Vertical Array Versus Single Transducer Target Strength 15 dB

The depth average signal level at 1.5 km for the array is 4 dB greater than for the single transducer (figure 7). Since the echo field consists of the same modes for either transmitting configuration, the depth average echo level should be 4 dB greater or 95 dB//1 μPa.

The echo decay beyond 1.5 km is determined for the two cases by equation (2).

Echo Decay dB/distance octave		Incident Level Decay dB/distance octave		Echo Propagation Loss VS Range dB/distance octave. (2)
-22.6	=	-11.3	+	-11.3 Single Transducer
-15.3	=	-4.0	+	-11.3 Array

The echo-decay rates for the two configurations are combined with the corresponding echo levels for a target at 1.5 km to form the two echo level versus range curves shown in figure 13.

The reverberation levels versus range for the two configurations are obtained from figure 11.

It is evident from figure 13, that the echo to reverberation levels for the single transducer, in contrast to the array case, become markedly worse with increasing range (this would improve, however, when the mode content of the single transducer field is reduced to low-order modes or when transition takes place from the reverberation zone to the ambient noise zone). It is also evident that the slower rate of echo decay for the array reduces the reverberation limited regions. This is illustrated in figure 14, where for a target strength of 20 dB, an array would allow tracking the target through what is the reverberation limited region for the single transducer.

Another possibility for improvement over a single transducer is revealed by examining the vertical structure of reverberation (see figure 9). It is seen that depth segments are present over the aperture of the

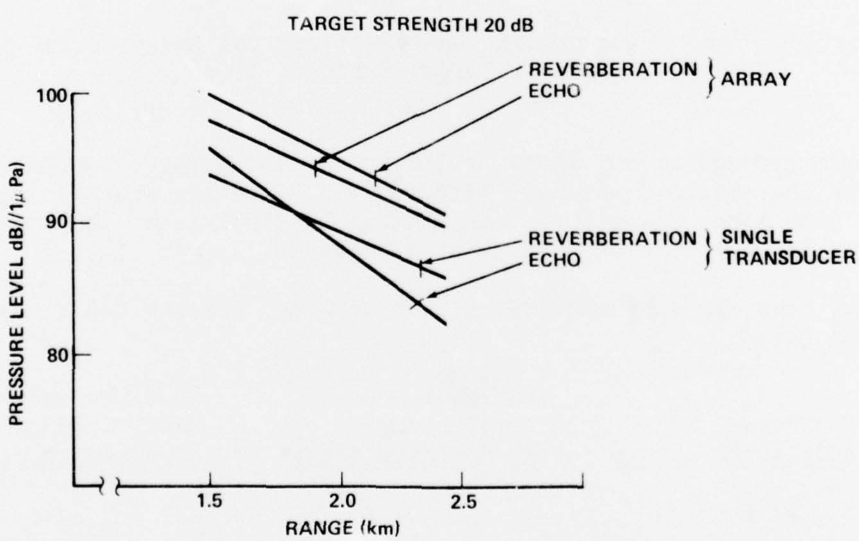

Figure 14. Echo to Reverberation Level Vertical Array Versus Single Transducer Target Strength 20 dB

receiving array, where differences between minimum and maximum levels are from 5 to 8 dB. Selectivity of receivers where minimum reverberation levels occur could provide a means for improving echo to reverberation levels.

ECHO TO NOISE

The results of the section on signal field demonstrate the potential of a vertical array to produce greater average and peak levels than would a single transducer. This implies that under the given conditions, a target echo would be greater for the array case. Thus for a noise background situation, the vertical array potentially would allow detection at longer ranges than would a single transducer.

Mode Enhancement Techniques – METS

The potential gains in echo-to-background levels from a vertical array would be even greater if mode enhancement techniques could be used in both transmitting and receiving. In transmitting, modes favored by the propagation conditions could be enhanced and manipulated to produce maximum signal levels within suspected segments of the water column. Resulting echo levels would be greater. In receiving, modes contained in the echo could be enhanced which have maximum amplitudes at depth segments where minimum reverberation or ambient noise levels occur.

CONCLUSIONS

Experimental and theoretical results are reported on shallow-water propagation and reverberation of 1700 Hz sound produced by a vertical transmitting array and a single transducer. Aspects of normal mode theory are applied to explain the results.

It is found that the signal field of the array is predominantly of low-order modes and decays at a much slower rate than the high-mode-dominated field of the single transducer. Thus, by enhancing low-order modes (those favored by the channel) a vertical array can produce greater average and peak values at a given range than a single transducer having the same input power.

It is also found that for equal input power, the level of reverberation for the array is greater, but that the decay rates for the two are approximately the same. The similarity in decay for reverberation but difference in decay for signal has sonar implications. Example calculations of echo to reverberation versus range show that echo-to-reverberation

levels are markedly greater for a vertical array than for a single transducer.

It is noted that the sonar implications discussed have been based on data that were envelope detected. Neither correlation properties of the echo, nor of reverberation, have entered the discussion. These considerations would weigh even more so in favor of a vertical array. In fact, the vertical correlation of reverberation versus hydrophone spacing has been examined and is the subject of another report.

The use of a vertical array to improve the efficiency of transmitting a signal, and to increase the signal-to-noise or echo-to-reverberation levels, is a form of mode enhancing. Further exploration of Mode Enhancement Techniques and their application to sonar design and operation are being pursued.

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